

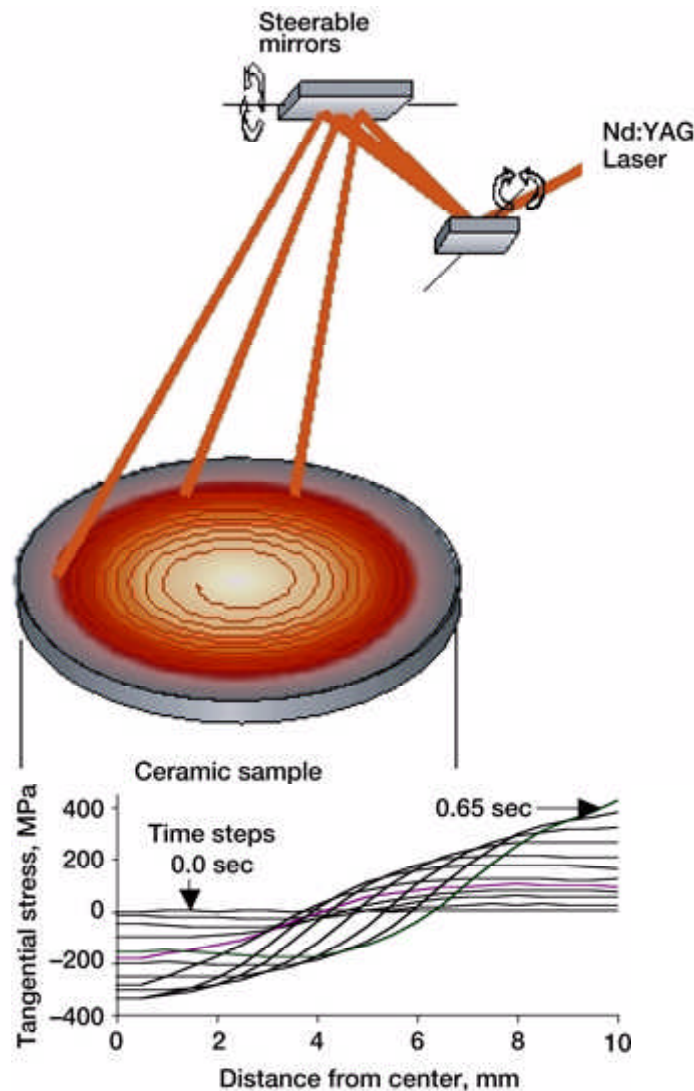
Integrity of Ceramic Parts Predicted When Loads and Temperatures Fluctuate Over Time

Brittle materials are being used, and being considered for use, for a wide variety of high-performance applications that operate in harsh environments, including static and rotating turbine parts for unmanned aerial vehicles, auxiliary power units, and distributed power generation. Other applications include thermal protection systems, dental prosthetics, fuel cells, oxygen transport membranes, radomes, and microelectromechanical systems (MEMS). In order for these high-technology ceramics to be used successfully for structural applications that push the envelope of materials capabilities, design engineers must consider that brittle materials are designed and analyzed differently than metallic materials. Unlike ductile metals, brittle materials display a stochastic strength response because of the combination of low fracture toughness and the random nature of the size, orientation, and distribution of inherent microscopic flaws. This plus the fact that the strength of a component under load may degrade over time because of slow crack growth means that a probabilistic-based life-prediction methodology must be used when the tradeoffs of failure probability, performance, and useful life are being optimized. The CARES/*Life* code (which was developed at the NASA Glenn Research Center) predicts the probability of ceramic components failing from spontaneous catastrophic rupture when these components are subjected to multiaxial loading and slow crack growth conditions. Enhancements to CARES/*Life* now allow for the component survival probability to be calculated when loading and temperature vary over time. This capability is referred to as transient reliability analysis and can be used to predict component reliability (probability of survival) for situations such as thermal shock, startup and shutdown conditions in heat engines, and cyclic loading. The methodology has been developed with the following features:

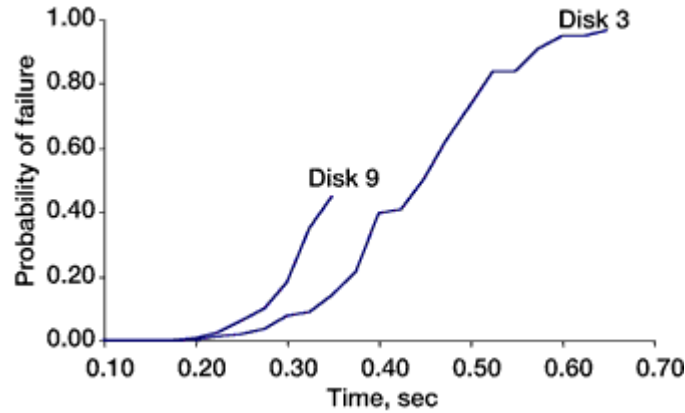
- Transient cyclic fatigue modeling
- Ability to efficiently compute transient reliability for any number of loading cycles
- Transient proof-testing analysis capability
- Ability to account for fatigue and Weibull parameters that change over the operating temperature range

This technology is considerably more sophisticated than the common approach of making predictions based on a maximum stressed point at some snapshot in time. Instead, in predicting the probability of survival, it considers the whole history of loading and the multiaxial stress distribution throughout the entire component. The probability-of-survival algorithm uses results from transient finite element analysis, where loading profiles are broken into discrete time steps.

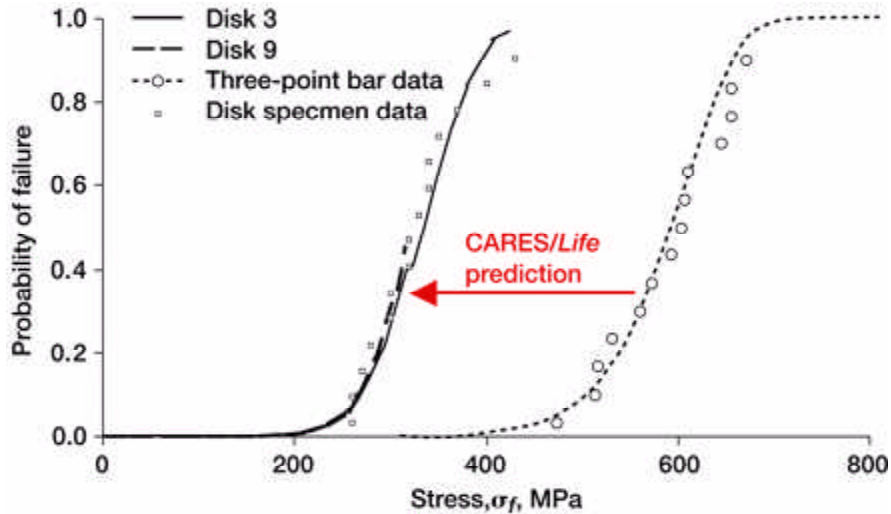
The figures show two examples that demonstrate some of these capabilities: the first four figures show thermal shocked silicon nitride disks in fast-fracture (where material strength does not degrade over time because of slow crack growth), and the last two figures show a silicon nitride turbine vane experiencing engine startup/shutdown conditions. These figures are described in more detail in the following paragraphs.



Left: Example of a thin silicon nitride disk under thermal shock. The schematic is of the laser upshock technique (experimental data from the literature). Copyright Uwe Rettig; used with permission. Right: Transient tangential stress profile of a silicon nitride disk under thermal shock. Time steps range from 0.0 to 0.65 sec. Not all time steps are shown.



CARES/Life predicted failure probability as a function of time for disk specimens 3 and 9. The predictions are based on the transient stress profile (see the right figure on the preceding page) and a finite element model of the disk. Shown are predictions for each discrete time step (which are connected by straight line segments).

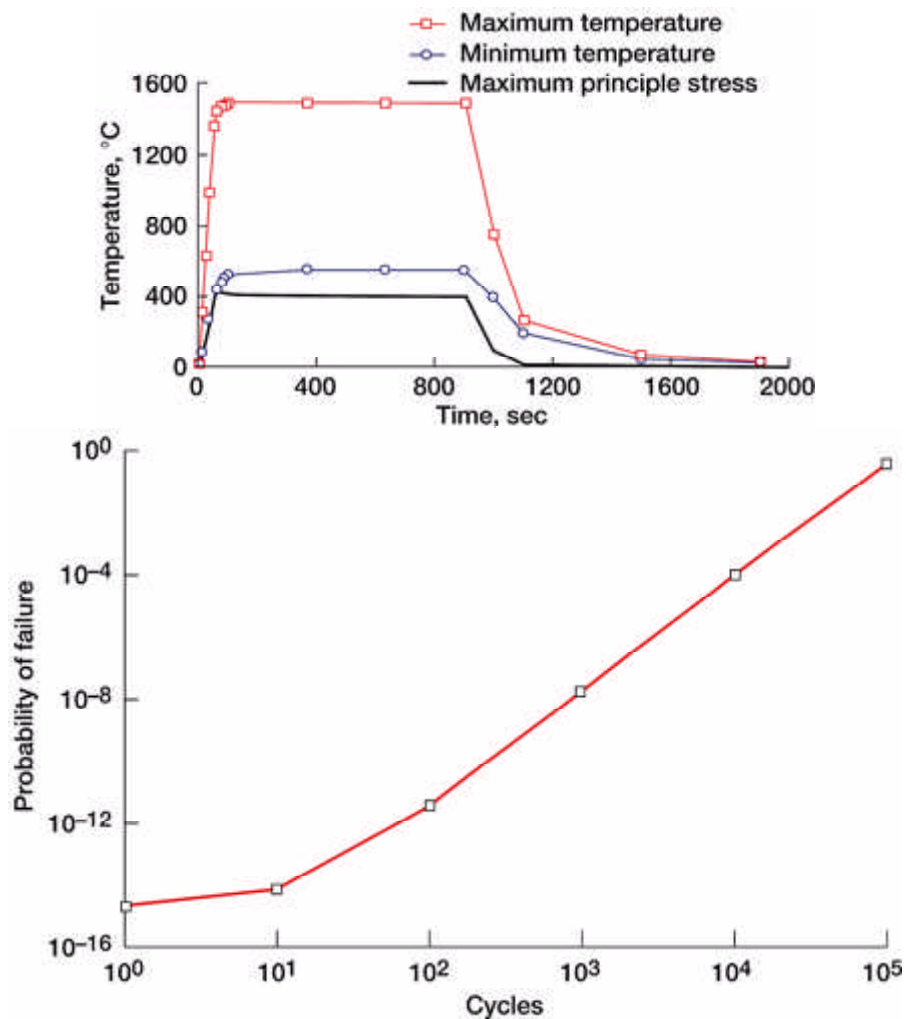


Silicon nitride disks under thermal shock. Failure probability of disk versus maximum stress predicted using CARES/Life finite element analysis and experimental results from three-point flexure bar data. Experimental rupture data are shown as discrete points. The disk prediction shown was based on the analysis of disks 3 and 9.

The preceding figures are an example of thin silicon nitride disks (20 mm diameter by 0.3 mm) rapidly heated by a laser. The experimental data were taken from the literature. The first figure (upper left) is a schematic of the laser heating method. Starting at the center of the disk, the laser spirals out towards the edge of the disk over a time interval of approximately 1 sec. The heating of the central portion of the disk causes high tangential stresses along the edge of the disk. The second figure (upper right) shows the transient tangential stresses versus distance as a function of time for a particular disk. The third figure (center) shows the CARES/Life predictions as a function of time for two of the ruptured disks. These predictions result from a finite element model of the disk loaded with the measured thermal profile of a given disk (in this case, disks 3 and 9) as a function of time. The fourth figure (bottom) shows the transient CARES/Life predictions as a

function of stress compared with experimental data. The disk prediction shown is based on an analysis of disks 3 and 9. The three-point flexure bar data were used to calibrate (characterize the material stochastic fracture behavior of) the CARES/*Life* probabilistic models.

The final figures (following) show the transient reliability analysis for a silicon nitride stator vane during the turbine startup/shutdown cycle. The top figure shows the maximum vane temperatures and stresses over the startup-shutdown cycle. The bottom figure is the predicted (power law) failure probability versus the number of startup-shutdown cycles. The significance of this example is that it shows the ability to make lifetime predictions for situations where fatigue and strength modeling parameters are changing (with temperature) over the loading cycle.



Top: Maximum temperatures and stresses versus time for a simulated startup-shutdown cycle of a ceramic turbine vane. Bottom: Predicted probability of failure versus the number of startup-shutdown cycles for the ceramic turbine vane.

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